Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 10 (2011) 971–976
Engineering Procedia

ICM11

Assessment of fatigue crack growth data available for materials from Portuguese bridges based on UniGrow model

N. Nik Abdullah [a*], José F.O. Correia [b,c], Abílio M.P. de Jesus [b,c]
Mohammad Hadi Hafezi [a], S. Abdullah[a]

[a] *Department of Mechanical and Material Engineering, 43600 UKM Bangi, Selangor, Malaysia*
[b]*UCVE/IDMEC - Pólo FEUP, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*
[c]*Engineering Department, ECT-UTAD, Quinta dos Prados, 5001-801 Vila Rea, Portugal*

Abstract

Fatigue crack growth models based on elastic–plastic stress–strain histories at the crack tip region and strain-life damage models have been proposed. The UniGrow model fits this particular class of fatigue crack propagation models. The residual stresses developed at the crack tip play a central role in these models, since they are used to assess the actual crack driving force, taking into account mean stress and loading sequential effects. The performance of the UniGrow model is assessed based on available experimental constant amplitude crack propagation data, derived for several metallic materials from representative Portuguese bridges. Key issues in fatigue crack growth prediction, using the UniGrow model, are discussed, in particular the residual stress computation.

Keywords: Crack propagation; Portuguese Trezoi bridge steels; UniGrow model; Residual stresses; Finite element analysis.

1. Introduction

The research on fatigue of materials and structures has deserved great interest both by academia and industry. Fatigue has been investigated for more than 150 years and still is a hot topic in research [1]. In particular, the investigation on fatigue crack propagation is not fully accomplished, despite the great developments achieved in the last decades. Paris [2] is considered the first one to establish a direct correlation between the fatigue crack propagation and a Fracture Mechanics parameter – the stress

* Corresponding author. Tel.: +6 (03) 8921 6503/6450; fax: +6 (03) 8925 9659
E-mail address: enikkeister@gmail.com.

1877-7058 © 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of ICM11 doi:10.1016/j.proeng.2011.04.160

intensity factor, leading to the so-called Paris's law. Since then, the Paris' law has been used extensively to model fatigue crack growth under constant amplitude loading. However, the Paris's law shows several limitations, namely it only models the stable crack propagation, excluding near threshold and near unstable crack propagation regimes. Also, the stress ratio effects are not accounted in the Paris's law. Many other fatigue crack propagation laws have been proposed to overcome the limitations of the Paris's law and also to deal with variable amplitude loading [3]. The proposed fatigue models differ on the number of variables involved and the number of parameters required to be identified by curve fitting.

Local strain-based approaches to fatigue [4-7] have been assumed as an alternative to Fracture Mechanics based fatigue crack propagation models. Local strain-based approaches to fatigue are often applied to model the crack initiation on notched components [8]. Some authors [9-14] have proposed a relation between the local strain-based approaches to fatigue and the Fracture Mechanics based fatigue crack propagation models. They assume crack propagation as a process of continuous re-initializations (failure of consecutive representative materials elements). The resulting crack propagation model has been demonstrated to be able of correlation of crack propagation data from several sources, including the stress ratio effects. The crack tip stress-strain fields are computed using elastoplastic analysis, which are used together a fatigue damage law to predict the failure of representative material elements. The simplified method of Neuber [15] may be used to compute the elastoplastic stress field at the crack tip vicinity using the elastic stress distribution given by the Facture Mechanics [11, 16-17].

This paper proposes the assessment of the model proposed recently by Noroozi *et al.* [11-13] to model fatigue crack propagation, based on the local strain approach to fatigue. This model has been denoted as UniGrow model and it has been classified as a residual stress based crack propagation model [18]. The model is applied to derive fatigue crack propagation data for two materials from Portuguese bridges, for distinct stress R-ratios. Results are compared with the available experimental data [19]. The required strain-life data was obtained by the authors and was already published in the literature [19]. The representative material element size is assessed. Also, the residual stress field is analyzed for distinct crack sizes and stress R-Ratios. The elastoplastic stresses at the vicinity of the crack tip, computed using simplified formulae, are compared with the stresses computed using a elastoplastic finite element analyses of the specimens used in the experimental program to derive the crack propagation data.

2. Overview of the UniGrow model

The UniGrow model was proposed by Noroozi *et al.* [11] based on the following assumptions:

- The material is composed of elementary particles of a finite dimension ρ^*. It represents an elementary material block size, below which material cannot be regarded as a continuum.
- The fatigue crack tip is considered equivalent to a notch with radius ρ^*.
- The fatigue crack growth process is considered as successive crack increments due to crack re-initiations over the distance ρ^*.
- The fatigue crack growth rate can be determined as:

$$da/dN = \rho^* / N_f \tag{1}$$

where N_f is the number of cycles required to fail the material over the distance ρ^*, which can be determined using the Smith–Watson–Topper [7] fatigue damage parameter:

$$\sigma_{max}\,\Delta\varepsilon/2 = \left(\sigma'_f\right)^2 \left(2N_f\right)^{2b} / E + \sigma'_f \varepsilon'_f \left(2N_f\right)^{b+c} \tag{2}$$

The maximum stress σ_{max} and the strain range $\Delta\varepsilon$ have to be evaluated as the average values at the elementary material block size, ρ^*, taking into account an elastoplastic analysis.

To compute the elastoplastic stresses and strains at the elementary material blocks ahead the crack tip, Noroozi *et al.* [11, 12] proposed the following procedure:

- The elastic stresses are computed ahead the crack tip using the Creager-Paris [20] solution for a crack with a tip radius ρ^*, using the applied stress intensity factors.
- The actual elastoplastic stresses and strains, ahead the crack tip, are computed using the Neuber approach [15]. Multiaxial approaches may be adopted using the procedures presented by Moftakhar *et al.* [16] and Reinhard *et al.* [17].
- The residual stress distribution ahead the crack tip is computed using the actual elastoplastic stresses computed at the end of the first load reversal and subsequent cyclic elastoplastic stress range, $\sigma_r = \sigma_{max} - \Delta\sigma$.
- The residual stress distribution computed ahead the crack tip is assumed to be applied on crack faces, behind the crack tip, in a symmetric way. The residual stress intensity factor, K_r, is computed using the weight function method [21].
- The applied stress intensity factor (maximum and range values) is corrected using the residual stress intensity value, resulting the total values, $K_{max,tot}$ and ΔK_{tot} [11,12].
- Using the total values of the stress intensity factors, the first and second steps before are repeated to determine the corrected values for the maximum actual stress and actual strain range at the material representative elements. Then, Equations (2) and (1) are applied to compute the crack growth rate.

The described methodology does not allow close-form solutions for the crack propagation rates. However, introducing some simplified assumptions on elastoplastic conditions (e.g. predominantly elastic behavior) it is possible to derive close-form solutions for the crack propagation rates based on a two-parameters crack driving force [11, 12]. In this paper, the full solution of the methodology proposed by Noroozi *et al.* [11] is followed. Besides the elastoplastic cyclic and fatigue properties of the material, the UniGrow model requires the definition of the elementary material block size, ρ^*. An iterative process is used to compute ρ^*. This parameter is computed using a try and error procedure in order a good correlation of the experimental crack growth data is obtained. The simplified elastoplastic analysis, based on Creager-Paris [20] and multiaxial Neuber's approach [15-17] is only used to compute the elastoplastic stress-strain field in the first elementary material block size ahead the crack. The residual stress distribution ahead the crack tip was computed using elastoplastic finite element analysis, since inconsistencies were found in the analytical residual stress distributions.

3. Materials and basic fatigue data

Two materials are considered in this study, namely a puddle iron from the Portuguese Fão bridge and a construction steel from the Portuguese Trezói bridge. The Fão bridge is a riveted metallic road bridge located at Esposende and was inaugurated in 1892. The Trezói bridge is a riveted metallic railway bridge located at Beira Alta railway line. This bridge was inaugurated in 1956 and was built using construction steel. The cyclic and strain-life properties of these two materials were evaluated and are summarized in Table 1. Fatigue crack growth rates of the materials were determined using the compact tension (CT) specimens (width, W=50 mm; thickness, B=8 mm) following the ASTM E647 standard, for several stress R-ratios. The crack propagation data of the material from Fão bridge shows significant scatter due to the significant amount of heterogeneities. This material shows more sensitivity to the stress ratio than the material from the Trezói bridge. Figure 1 shows the crack propagation data for the two materials, for stress ratios R=0, R=0.25 and R=0.5. Details about the properties evaluation can be found in reference [19].

Table 1. Cyclic elastoplastic and strain-life properties of the materials from the Fão and Trezói bridges.

Material	*E (GPa)*	ν	*K' (Pa)*	*n'*	σ_f' (MPa)	ε_f'	*b*	*c*
Fão	198.70	0.265	818.47	0.140	828.30	0.0530	-0.1134	-0.5113
Trezói	198.49	0.320	821.3	0.177	609.70	1.4733	-0.092	-0.8137

4. Results and discussion

Figure 1 compares the experimental fatigue crack propagation rates with the predictions resulting from the UniGrow model. The predictions resulted from an elementary material block size, ρ^*, equal to 4×10^{-4} m and 8.5×10^{-4} m, respectively for the Fão and Trezói bridge materials. Despite the higher scatter observed in the experimental data, the predictions proposed for the material of the Fão bridge are more consistent with the experimental data. The predictions obtained for the material of Trezói bridge overestimates the crack propagation rate for R=0.5. It seems that the UniGrow model tends to overestimates the stress ratio effects for materials exhibiting crack propagation rates with low sensibility to stress ratio effects. The stress ratio effects are captured by the UniGrow model through the SWT parameter as well by the residual stresses effects. The SWT – N_f relation available for the material from the Trezói bridge is based on a very limited number of data points (10 points) which may have an important influence on results. For the material from the Fão bridge, a total of 34 data points were used to define the SWT – N_f relation covering a high range of fatigue lives, which makes the predictions of the UniGrow model more significant for this material.

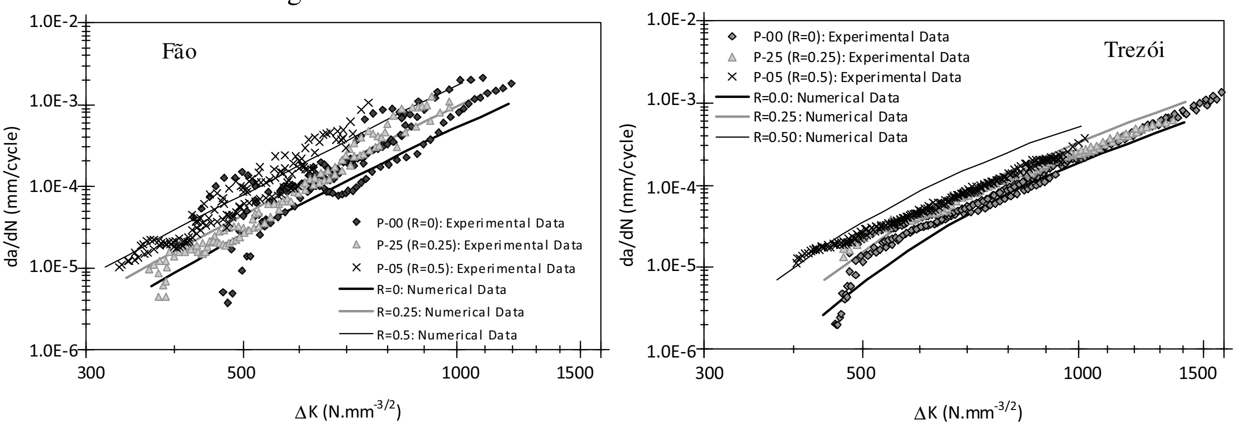

Figure 1. Fatigue crack propagation data for the materials from the Fão and Trezói materials: experimental data and predictions.

Since the UniGrow model is a residual stress based propagation model, the accuracy of the residual stress estimation is essential. Therefore, a comparison between the results from the analytical approach for the residual stresses, described in Section 2, and the results from finite element analyses was carried out. A parametric finite element model of the CT specimen was built taken into account the actual geometry of the crack underlying the UniGrow model. Elastoplastic analyses were performed using the J2 yield plasticity with multilinear kinematic hardening. The material response was fitted to the Ramber-Osgood description of the material (parameters on Table 1). Rigid-to-flexible contact was used to simulate the pin loading in the CT specimen. Figure 2 compares the residual stresses ahead the crack tip from the numerical and analytical analysis. Numerical residual stresses were derived from a sequence of two load steps. From the analysis of the Figure 2, one may verify that for R=0 the residual stresses from numerical and analytical analysis are in close agreement for distances near the crack tip. However, for higher distances the analytical solution gives an asymptotic behavior leading to a significantly higher compressive zone leading to an overestimation of the compressive residual stress intensity factor, K_r. The size of the compressive zone increases with the crack size. However, for R=0.5 the analytical approach shows a reverse evolution meaning an inconsistent prediction. The numerical model is consistent for both R=0 and R=0.5. Furthermore, the extension of the residual stress zone for R=0.5 seems to be overestimated by the analytical model, since for this stress ratio level the residual stresses should be almost negligible. The numerical model only predicts marginal residual compressive stresses for R=0.5. The analytical model does not capture the stress redistribution that occurs at the crack tip vicinity. Therefore, the predictions presented on Fig. 1 were based on residual stresses from the numerical analysis. The analytical approach was only used to simulate the elastoplastic behavior at the first representative material element ahead the crack tip.

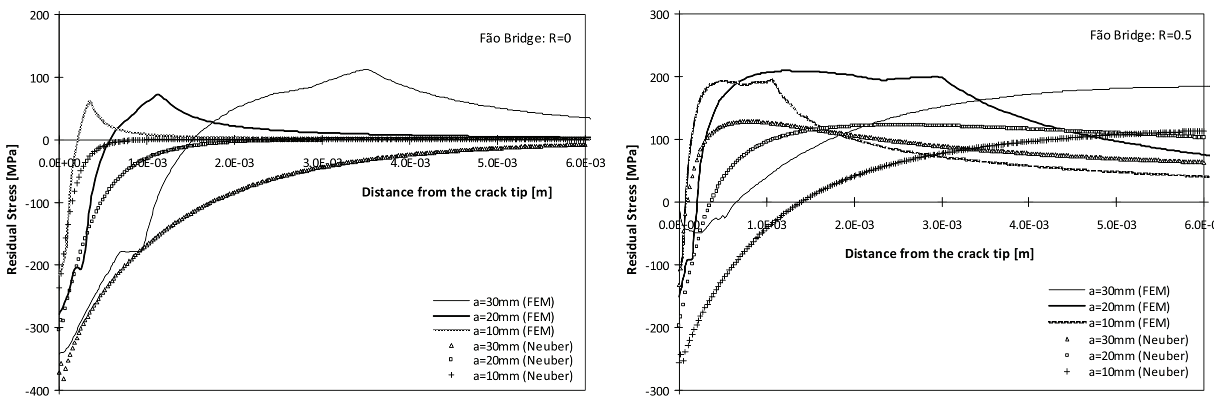

Figure 2. Residual stress distributions – comparison of analytical and numerical results for the material from the Fão bridge.

5. Conclusions

A crack propagation model based on a local strain approach – the UniGrow model – was assessed using available experimental fatigue crack growth data available for two materials from Portuguese bridges, namely the puddle iron from the Fão bridge and the construction steel from the Trezói bridge. The UniGrow model produced satisfactory predictions of the crack growth of the material from the Fão bridge, accounting conveniently for the stress ratio effects. Concerning the material from the Trezói bridge, the crack growth rates are overestimated for stress ratios R=0.5. The less satisfactory performance of the UniGrow model for the material of the Trezói bridge may be in part attributed to the very limited experimental data regarding the strain-life behavior of the material. The predictions were based on elementary material block sizes, ρ^*, equal to 4×10^{-4} m and 8.5×10^{-4} m, respectively for the Fão and Trezói materials, which are in the same order of magnitude, but significantly lower than the values proposed by Noroozi *et al.* [12] for the 4340 steel ($\rho^*=2\times10^{-6}$ m).

The performance of the analytical procedure originally proposed in the UniGrow model to compute the residual stresses was checked by means of an alternative finite element analysis. The comparison between the numerical and analytical results highlighted some inconsistencies in the analytical results. The analytical procedure produce reliable results at the crack notch root, but the residual stress distribution along the crack front path (away the crack notch root) seems to be inconsistent, which is in part justified by the incapacity of the analytical model to handle with the stress redistribution due to yielding. In particular, for R=0, the analytical model overestimates the compressive zone at the crack tip vicinity.

References

[1] Schütz, W. A History of Fatigue. *Engineering Fracture Mechanics* 1996; **54**: 263-300.

[2] Paris, PC, Gomez, M, Anderson, WE. A rational analytic theory of fatigue. *Trend Engineering* 1961; **13**: 9-14.

[3] Beden, SM, Abdullah, S, Ariffin, AK. Review of Fatigue Crack Propagation Models for Metallic Components. *European Journal of Scientific Research* 2009; **28**: 364-97

[4] Coffin, LF. A study of the effects of the cyclic thermal stresses on a ductile metal. *Translations of the ASME* 1954; **76**: 931-50.

[5] Manson, SS. Behaviour of materials under conditions of thermal stress. *NACA TN-2933*, National Advisory Committee for Aeronautics; 1954.

[6] Morrow, JD. Cyclic plastic strain energy and fatigue of metals. *Int. Friction, Damping and Cyclic Plasticity*, ASTM STP 378; 1965, p. 45-87.

[7] Smith, KN, Watson, P, Topper, TH. A Stress-Strain Function for the Fatigue of Metals. *Journal of Materials* 1970; **5**(4): 767-78.

[8] Shang, D-G, Wang, D-K, Li, M, Yao, W-X. Local stress–strain field intensity approach to fatigue life prediction under random cyclic loading. *International Journal of Fatigue* 2001; **23**: 903–10.

[9] Glinka, G. A notch stress-strain analysis approach to fatigue crack growth. *Engineering Fracture Mechanics* 1985; **21**: 245-61.

[10] Peeker, E, Niemi, E. Fatigue crack propagation model based on a local strain approach. *Journal of Constructional Steel Research* 1999; **49**: 139–55.

[11] Noroozi, AH, Glinka, G, and Lambert S. A two parameter driving force for fatigue crack growth analysis. *International Journal of Fatigue* 2005; **27**: 1277-96.

[12] Noroozi, AH, Glinka, G, and Lambert, S., A study of the stress ratio effects on fatigue crack growth using the unified two-parameter fatigue crack growth driving force, *International Journal of Fatigue* 2007; **29**: 1616-33.

[13] Noroozi, AH, Glinka, G, and Lambert, S. Prediction of fatigue crack growth under constant amplitude loading and a single overload based on elasto-plastic crack tip stresses and strains. *Engineering Fracture Mechanics* 2008; **75**: 188-06.

[14] Hurley, PJ, Evans, WJ. A methodology for predicting fatigue crack propagation rates in titanium based on damage accumulation. *Scripta Materialia* 2007; **56**: 681–684.

[15] Neuber, H. Theory of stress concentration for shear-strained prismatic bodies with arbitrary nonlinear stress–strain law. *Trans ASME Journal of Applied Mechanics* 1961; **28**: 544–51.

[16] Moftakhar, A, Buczynski, A, Glinka, G. Calculation of elasto-plastic strains and stresses in notches under multiaxial loading. *International Journal of Fracture* 1995; **70**: 357-73.

[17] Reinhard, W, Moftakhar, A, Glinka, G. An Efficient Method for Calculating Multiaxial Elasto-Plastic Notch Tip Strains and Stresses under Proportional Loading. *Fatigue and Fracture Mechanics* 1997; **27**, ASTM STP 1296, RS Piascik, JC Newman, NE Dowling, Eds., American Society for Testing and Materials, p. 613-29.

[18] Mikheevskiy, S, Glinka, G. Elastic–plastic fatigue crack growth analysis under variable amplitude loading spectra. *International Journal of Fatigue* 2009; **31**: 1828–36.

[19] De Jesus, AMP, Silva, ALL, Figueiredo MV, Correia, JAFO, Ribeiro, AS, Fernandes, AA. Strain-life and crack propagation fatigue data from several Portuguese old metallic riveted bridges. *Engineering Failure Analysis* 2010; **17**: 1495–99.

[20] Creager, M, Paris, PC. Elastic field equations for blunt cracks with reference to stress corrosion cracking. *International Journal of Fracture Mechanics* 1967; **3**: 247–52.

[21] Glinka, G. Development of weight functions and computer integration procedures for calculating stress intensity factors around cracks subjected to complex stress fields. *Progress Report No.1: Stress and Fatigue-Fracture Design*, Petersburg Ontario, Canada; 1996.